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## Strategic approach to research in the Meteorological Office

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### Summary

*The success of the Meteorological Office builds on the excellence of its research. This article describes the aims of the Research Programme, and its organization and management. It summarizes the motivation and key strengths of the Office's Research Division and it highlights growth areas for research during the 1990s.*

### 1. Introduction

#### 1.1 Nature and size of the Research Programme

The Director of Research is responsible for a broad programme of both research and development. There is no purely curiosity-driven research within the Programme but the nature of the Meteorological Office's operational requirements is such as to require fundamental as well as applied research. The Research Directorate is composed of three Divisions: Short-range Forecasting Research (S-Division), Extended-range Forecasting and Climate Research (E-Division) and Atmospheric Processes Research (P-Division). The main sources of funding are the Ministry of Defence (MOD) and Department of Environment (DoE). Eleven per cent of Office staff work in the Research Directorate. In addition the Director of Research has programme responsibility for Observational Instrumentation research carried out by a small team within the budget of the Director of Operations. A few other Operations staff also contribute to research projects. In return, some staff of the Research Directorate support the operational implementation of recently developed systems.

### 2. Strategic approach

#### 2.1 What determines the size of the Research Programme?

Improvements in the quality, range, effectiveness and efficiency of meteorological services are required by the MOD, other government departments, the Civil Aviation Authority (CAA), industry and the general public. A key requirement is the development of weather forecasting products. Another is the maintenance of a broad and up-to-date knowledge base for provision of advice on meteorology and climate to government. Fulfilment of these requirements calls for a diversity of expertise and a wide range of research activities of a viable size. Factors taken into account in determining the overall size of the Research Programme are:

- (a) the anticipated requirements over a 10-year time span,
- (b) the amount of research conducted by other National Meteorological Services and the need to remain competitive with them, and
- (c) the magnitude of the total turnover of the Meteorological Office.

## 2.2 Statement of Aims

The primary aim of the Meteorological Office Research Directorate is to support and develop the services provided by the Office by maintaining a sufficient base of scientific expertise to enable improvement of capabilities for observing, analysing and predicting the atmosphere and oceans.

## 2.3 The integrated nature of research and operations

A strength of the Office, and one of the ways it differs from most other National Meteorological Services, is the integrated management of its research and operations. This ensures that research carried out in-house is responsive to operational requirements (and vice versa) not only in the setting of objectives but also in the day-to-day interactions of the staff. The research contributes to a core capability that benefits the whole range of customers, both military and civil.

## 2.4 Quality research underpinning the Meteorological Office's reputation

The quality of research within the Meteorological Office has been a major factor in determining the high regard in which it is held nationally and internationally. Research of a high standard provides credibility and underpinning of the quality and competitive edge of its present and future services. It also provides an attractive framework for recruiting, training and retaining high-calibre staff for the Office as a whole.

## 2.5 Relationship between research conducted in-house and externally

Operational meteorological requirements continue to pose major scientific challenges and so the approach has to be one of quality science carried out within long-term programmes by scientists in close contact with the practical demands of operational forecasting and services. This is best achieved by in-house research, but the range of expertise required is such that there is considerable collaboration with other organizations (Table I). It is to our mutual advantage that meteorological research in universities and elsewhere is strengthened and that collaborative links are further developed. Contracted research is also carried out at the European Centre for Medium-range Weather Forecasts (ECMWF). The Office provides a focus for the national research effort related to observation and prediction of weather and climate. It is a national centre of excellence for research into weather and climate, and also for modelling of the oceans.

## 2.6 Importance of international collaboration in research

Meteorology has a strong tradition of international collaboration both operationally and in research. This is not only for the obvious reason that many atmospheric events take place on a global stage but also because the

task of observing the atmosphere is a massive undertaking whether it be on a global scale or on the scale of individual clouds and weather systems. The Meteorological Office is therefore involved, in some cases as prime mover, in many collaborative research projects both bilaterally with scientists in other nations in Europe, and further afield, and also as part of major international programmes such as the World Climate Research Programme (WCRP). The C-130 aircraft of the Meteorological Research Flight (see section 5) is a key observational facility that provides a passport for participation in international field experiments.

## 2.7 High-calibre staff as the Meteorological Office's greatest asset

The collective expertise, understanding, flair and dedication of the staff is the Office's greatest asset. The highest priority for the Research Directorate is to continue to attract and retain research scientists of high calibre; this depends on the maintenance of a stable research programme whose science is not only useful but also recognized as being scientifically excellent. In order to carry out the kind of research that will enable the Office to remain at the forefront of the science it is necessary for career planning to give opportunities and incentives for innovative scientists and technical specialists to advance and acquire a reputation within specific areas of expertise.

## 3. Management of the Research Programme

### 3.1 Factors influencing the content of the Research Programme

The long-term strategic context of the Research Programme is determined by the Director of Research in the light of:

- (a) the broad user requirements articulated by the Director of Operations and to a lesser extent by the Director of Commercial Services, and
- (b) an understanding within the Research Divisions of the scientific opportunities.

Although specific efforts are made to inform end users about the Research Programme and in some cases to undertake special research for them, the major proportion of the research is carried out to create the Office's core capability, with the Director of Operations serving as the main proxy customer. The understanding and prediction of climate and pollution-related processes are treated separately as part of the Office's Public Meteorological Services (PMS); climate prediction research is also undertaken directly on behalf of the DoE as part of the Climate Prediction Programme (CPP). Although funded on a year-by-year basis, the CPP is seen by DoE as being a long-term programme. Opportunities are taken to make research products and expertise available for commercial exploitation when it

**Table 1.** Links with other UK-based activities

Topic	Met. Office Division	Main collaborating organization	Special linking mechanism
Oceanography	E	University of Oxford Rennell Centre PML	Hooke Institute, CPP, UK WOCE
Cryosphere	E	BAS, SPRI	CPP
Upper atmosphere	E	Universities of Cambridge and Oxford	Hooke Institute, UGAMP
Atmospheric chemistry	E, P	Universities of Cambridge and Oxford	Hooke Institute, UGAMP
Mesoscale meteorology	P	Universities of Reading and Leeds	JCMM
Clouds and radiation	P	UMIST and University of Reading	CPP, JCMM
Hydrological and land processes including carbon cycle	E	IH	MITRE, TIGER
Space instrumentation	O	RAL	
Use of data in models	S	ECMWF	
Weather radar	S	RAL, UMIST, IH, Universities of Salford, Essex, Lancaster and Edinburgh	

This is only a partial tabulation — many more links are maintained through CASE studentships, Gassiot grants and informal collaboration.

**KEY:**

BAS	British Antarctic Survey
CASE	Co-operative Award in Science and Engineering
CPP	DoE — funded Climate Prediction Programme at the Hadley Centre
ECMWF	European Centre for Medium-range Weather Forecasts
IH	Institute of Hydrology
JCMM	Joint Centre for Mesoscale Meteorology
MITRE	Meteorological Office/Institute of Hydrology Terrestrial Model
PML	Plymouth Marine Laboratory
RAL	Rutherford Appleton Laboratory
SPRI	Scott Polar Research Institute
TIGER	Terrestrial Initiative on Global Environmental Research
UGAMP	UK Universities Global Atmospheric Modelling
UMIST	University of Manchester Institute of Science and Technology
WOCE	World Ocean Circulation Experiment

can be done without jeopardizing the core activities. Efforts are made to secure sponsorship from industry and contracts, for example from the Commission for the European Communities (CEC), to conduct research that supports the core activities.

### 3.2 Formulation of the Research Programme as a series of projects

The Research Programme is formulated as individual Projects, 32 of them at present (see Table II), each led by a Project Manager at Grade 7 (or above). Project

proposals with resource requirements identified over a 3-year period are prepared or updated on a yearly basis by Project Managers each under the guidance of a Tasking Manager (generally the relevant Divisional Director) in the light of a series of discussions with key external and internal customers. The broad Research Programme is considered by the Meteorological Office Board of Management as part of the corporate planning procedure and is presented in detail to the Meteorological Research Sub-Committee in December each year.

### 3.3 Control of the Research Programme and the role of serendipity

The Director of Research is responsible for the execution of the Research Programme. He is provided with regular summaries of resource out-turn by his Budget Manager and quarterly summaries of progress by his Tasking Managers. Research by its very nature rarely goes according to plan. Important though plans are they must not be used as a straitjacket. Serendipity has to be exploited. Hence the Director of Research will use his judgement to authorize departures from the plan or even new starts or premature termination of projects if he deems it necessary in the interests of the customers and/or the broader strategy. Where major departures from the plan are necessary he will seek the approval of the Meteorological Office Board at which he reports quarterly on progress against targets specified in the Research Programme. On a day-to-day basis the research is line-managed within Divisions in a manner that relates to particular expertise or skills and/or facilities. Some individual Research Projects, however, cut across skill areas and even across Divisions. Project Managers are responsible for horizontal co-ordination of these activities within agreed resource allocations laid down in the Research Programme.

### 3.4 Attribution of research costs to customers

Each Research Project is cost accounted. Attribution of costs is spelled out in the Summary Tables attached to each Research Programme document and is open for scrutiny during the various consultative stages. Attribution is between:

- (a) Meteorological Office core,
- (b) the research component of the Public Meteorological Services, and
- (c) direct sponsorship by particular customers (DoE, CAA, Defence Services and Commercial Services).

The Director of Operations, as the customer for the core research, exploits the results to sustain and improve the quality of the services he is responsible for providing to the end customers, and he passes on an appropriate fraction of these research costs to his customers.

## 4. Evaluation of the Research Programme

### 4.1 The formal assessment of research

The Research Programme document, in addition to providing a description and justification of the work plan, gives costs and milestones. The Annual Research Progress Report prepared at the end of each financial year presents the corresponding out-turn and attainment of milestones in addition to summarizing the main achievements, publications completed, and deviations from plans. The excellence of the research is assessed by the Meteorological Research Sub-Committee. The chairman assigns an overall quality rating to projects in

the light of the members' markings and after appropriate discussion. Tasking Managers may revise their programmes accordingly.

### 4.2 Other more telling indicators of the value and quality of research

The value of research, especially long-term research of the kind so important to the Meteorological Office, is not easily represented by quantitative measures such as the attainment of short-term targets. Rather, the true value of the research is evident from the overall improvement of forecast accuracy over a period of years; it is also evident from time to time when, for example, the Office receives the accolade of becoming a World Area Forecast Centre for Civil Aviation, or when its Chief Executive is asked to chair a Working Group of the Intergovernmental Panel on Climate Change, or in the joint establishment with the DoE of the Hadley Centre which brought with it the contract for the 'DoE Climate Prediction Programme'. Accordingly it is important to avoid becoming beguiled by the quantitative aspects of the short-term targets or, indeed, spending too much time in operating complex evaluation procedures, except in the larger development projects where more formal project management techniques are used.

### 4.3 Lessons to be learned from evaluating the Research Programme

Although the quantitative aspects of the evaluation procedure should not be carried too far, the discipline of this approach is nevertheless a valuable means not only of sharpening up the conduct and presentation of research but also of identifying problems at an early stage. The kind of lessons that might be learned can be illustrated by some of our earlier successes and failures. For example, the successful development and application of the weather radar network in the United Kingdom was a result of an effective in-house research effort, close collaboration with external partners and timely and effective technology transfer to operational implementation. The slow progress with a related programme can be attributed to the premature contracting out to industry of a still-evolving methodology. Other projects, by contrast, have suffered from being continued in-house for too long. These are the kinds of problem evaluation procedures should identify at an early stage.

## 5. Motivation of the research in the main Functional Areas

### 5.1 Short-range forecasting research (S-Division)

The motivation of S-Division is to develop numerical weather and ocean prediction systems (including data quality control and analysis procedures, and forecasting models) so as to satisfy the needs of the Office in providing weather and ocean forecasting services to its

**Table II.** Project titles in 1991/92

**S-Division**

- Representation of atmospheric dynamics in numerical models
- Ocean forecast modelling
- The processing, quality control and assimilation of observations (including satellite data) for NWP
- Observation assessment studies
- Improvements to the operational global and regional NWP system
- Very-short-range weather forecasting
- Development of satellite image products
- Interpretation of satellite image products
- Interpretation of satellite and radar images
- Improvements to the operational mesoscale prediction system

**E-Division**

- Analysis, modelling and theoretical studies of the dynamics and photochemistry of the middle atmosphere
- Development of methods of extended-range forecasting
- Seasonal to multi-decadal climate variability
- Simulation of climate and climate change
- Ocean and sea-ice modelling
- Basic dynamical processes in rotating fluids
- Climate prediction programme
- Intergovernmental Panel on Climate Change
- Development and testing of parametrizations of physical processes for NWP and climate models

**P-Division**

- Observational verification of mesoscale processes
- Improved parametrizations of mesoscale processes
- Improved description of radiative processes
- Improved description of clouds and their occurrence
- Observational verification of boundary-layer models
- Development of boundary-layer models
- Development of specific forecasting techniques
- Improved description of atmospheric dispersion
- Nuclear Accident Response Model
- Measuring and predicting atmospheric composition
- Tactical decision aids

**O-Division**

- Space instrument concept and design evaluation
- Interpretation of satellite instrument data

customers. Research is also carried out to meet the specialized forecasting needs of particular customers, such as the Armed Forces and the CAA. There are increasing demands from users for more area-specific predictions of local weather phenomena. These are derived from numerical models themselves or through diagnostic procedures and/or by using detailed observations from space and special networks of earth-based sensors. Short-range forecasting is concerned with time-scales from hours to a few days. Medium-range forecasting research (4–10 days ahead) is contracted to ECMWF. Longer-range forecasting research is carried out in E-Division.

## 5.2 Extended-range forecasting and climate research (E-Division)

The motivation of E-Division, of which the Hadley Centre for Climate Prediction and Research forms the major part, is:

- (a) to develop extended-range forecasting techniques for predicting the weather over periods from a week to a season,
- (b) to develop and maintain an up-to-date knowledge base on the physics of climate and climate change enabling the Office to provide expert advice to Government,
- (c) to develop the art of modelling the coupled climate system including atmosphere, oceans, ice and land surface so as to predict climate changes resulting from both natural and man-made effects to the end of the next century, and
- (d) to develop and use observational databases to improve climate models, to understand climate fluctuations, and to detect climate change.

## 5.3 Atmospheric processes research (P-Division)

The motivation of P-Division is to provide expert background and guidance to ensure that the Office's services and products relating to both weather and climate benefit from advances within the wider meteorological community in the ability to represent and predict physical processes in the atmosphere. A range of strategic observational and theoretical studies is pursued to address key issues of relevance to the Office. In some cases the magnitude of the research tasks is such that participation in international programmes provides the most effective means to meet objectives.

## 5.4 Observational instrumentation research (O-Division)

The motivation of the research part of O-Division is to ensure that the satellite instrumentation employed, either directly by the Meteorological Office or indirectly by funding through, for example, space agencies, is cost-effective and soundly based on requirements. Advanced construction, calibration and validation work are undertaken to maintain a capability for ensuring that these requirements are met.

## 6. Key strengths

The Meteorological Office has over the years developed particular strengths that enable it to undertake research effectively. The strengths consist of a combination of specialized skills, facilities, infrastructure, etc. as follows:

### 6.1 Key strengths of the Meteorological Office as a whole

- The integrated management of research and operations.

- The numbers, quality and motivation of the staff.
- Very powerful computing facilities.
- A unified modelling facility (para. 6.1.1).
- Status as a Regional Telecommunications Hub of the World Meteorological Organization (WMO).
- Excellent training facilities.
- Responsibilities as the National Meteorological Service.
- National and international reputation and influence.

#### 6.1.1 Attributes of the Meteorological Office Unified Model

- Atmospheric and Ocean Model with data assimilation options.
- Global and limited area configurations.
- Extensive range of parametrizations including explicit clouds.
- General purpose software system allowing easy exchange of modules.
- User interface allowing easy use by scientists.
- Extensive diagnostic system.

### 6.2 Key strengths in S-Division

- Expertise in numerical modelling and data assimilation and in the processing and interpretation of satellite and radar data.
- Computing facilities — the research makes extensive use of the Office's supercomputer and graphics workstations.
- An operational software suite developed to carry out quality control, analysis, forecasting, post-processing and diagnostic monitoring, using a variety of remote-sensing and *in situ* observations.
- Mesoscale forecasting facilities for detailed forecasting in the British Isles; there is a broad base of experience in the manipulation of satellite and radar imagery.

### 6.3 Key strengths in E-Division

- Expertise in numerical modelling and interpretation of climate data.
- Supercomputing facilities — climate modelling has been developed on the main Office supercomputer and this facility is now supplemented by a dedicated supercomputer funded by DoE with powerful front-end facilities, mass storage and workstations.
- A coupled model of the atmosphere, oceans, ice and land surface — this forms the basic tool for climate research and prediction.
- An archive of climate data — experience exists within the office for blending remotely sensed and *in situ* observations to provide a properly analysed and quality-controlled climate database for research.

### 6.4 Key strengths in P-Division

- Expertise in carrying out field experiments, and in interpreting small-scale models in terms of the

physical processes that need to be represented in weather forecasting and climate models.

- Computing facilities — these allow for the use of numerical simulations of small-scale atmospheric motions to provide an overall description and understanding of processes that cannot be observed in their entirety.
- The instrumented C-130 research aircraft of the Meteorological Research Flight (para. 6.4.1) — data collected by this versatile aircraft at different levels within the troposphere underpin a large part of the research programme and provide a ticket for full participation in international collaborative projects.
- The Cardington balloon facility — this is a tethered balloon facility which carries instruments aloft for detailed study of parts of the atmosphere close to the ground.

#### 6.4.1 The Meteorological Office Research Flight (MRF)

The MRF is composed of an aircraft facility and four scientific groups which use the aircraft for a wide programme of atmospheric research. The large capacity and long endurance (up to 11 hours) of the C-130 make it ideal for the task. It is flown by RAF aircrew permanently based at MRF. The current research activities are in the areas of:

- The investigation of mesoscale phenomena.
- The characteristics and microphysical properties of clouds.
- The radiative transfer through clouds and cloud-free air.
- The generation of tropospheric ozone from man-made pollutants.

Some of these activities are undertaken jointly with other organizations.

### 6.5 Key strengths in the research part of O-Division

- Expertise in the design and construction of satellite instrumentation and in the interpretation of the data for meteorological purposes.
- The C-130 aircraft provides a test bed for field calibration and evaluation of new space instruments.
- Development laboratories — access is available to laboratories and environmental test facilities both at the Meteorological Office and at RAE Farnborough.

## 7. Science growth points — opportunities and challenges for the Meteorological Office

### 7.1 The enabling technologies

The 1990s will be a decade of expanding opportunities brought about by technological advances:

- (a) in computing, especially parallel computing and graphics workstations, and
- (b) in automated observing systems, especially but not exclusively, space-borne systems.

The opportunities lie in the better forecasting of both weather and climate.

## 7.2 The need to improve numerical models

One of the outstanding challenges of the 1990s will be to improve the performance of the numerical models used to predict weather and climate. This will require much greater understanding of a variety of dynamical and physical processes in the atmosphere, and the interactions between them, and the ability to represent these processes faithfully in practical numerical models. It will also require increases in computer power, both to allow use of more sophisticated representations, and to allow the resolution of the models to be increased.

## 7.3 The need to understand and parametrize physical processes

A particular challenge will be to improve the representation (parametrization) of mesoscale and cloud-scale processes in numerical models. This will call for the Office to redouble its efforts in the area of process studies using a combination of field measurements with the C-130 aircraft and special cloud-scale numerical models. The World Climate Research Programme is paying particular attention to these issues within the Global Energy and Water Cycle Experiment (GEWEX) and some of the Meteorological Office research will be undertaken within the context of this international programme.

## 7.4 The need to improve the exploitation of data, especially from satellites

Satellites are playing an increasingly important role, not only in providing global data for weather forecasting and for climate monitoring, but also for research into the processes that need to be represented in weather and climate models. The scientific community has underestimated the magnitude of the task of using data from satellites. The Office will strengthen its efforts in this area through involvement with the development and evaluation of space instrumentation, through the development of techniques for blending space and other observations to provide optimal analyses, and through the exploitation of these data in weather forecasting and for climate research. Four-dimensional data assimilation will be a priority area for further research.

## 7.5 The Meteorological Office role in climate research and prediction both regionally and globally

The Meteorological Office has a leading role nationally in the increasingly prominent field of climate research and prediction. There will be great benefits to the

nation, both economically and for policy formulation, in having a capability for predicting climate change due to both natural and man-made causes. It is government policy that this leadership shall also be exerted internationally through participation in appropriate international activities. This leadership will require a continuing programme of the highest scientific integrity and excellence.

## 7.6 The Meteorological Office role in the climate space segment

The Office is currently overseeing the national contribution to space programmes required for weather forecasting, through the European organization EUMETSAT and through bilateral arrangements with the USA. With the move towards a Global Climate Observing System, the Office will be well placed to play a similar role with regard to the new generation of operational space programmes for climate.

## 7.7 The increasing involvement of the Meteorological Office with the oceans

The close coupling of the oceans and the atmosphere is something that needs to be represented within numerical models whether they be required for predicting the state of the atmosphere or of the ocean. Increased effort into coupled atmosphere-ocean modelling and the use of appropriate observations will lead to important improvements in both long- and short-term prediction capability which in different ways will be of special interest to the DoE and the Navy. Collaboration with the Natural Environment Research Council (NERC) will be particularly appropriate in some aspects of the research.

## 7.8 The development of very-short-range weather forecasting methods

An aspect of weather forecasting that has great potential for improvement and commercial exploitation is very-short-range (0-12 hours) area-specific weather forecasting. This is the kind of forecasting that has to do with predicting extreme events. The Office has pioneered separately the development of very-fine-mesh forecasting models, and nowcasting techniques using imagery; these are key areas that will be brought together and developed for wider exploitation.

## 7.9 The bottom line

The above are all long-term research tasks. The operational success of the Meteorological Office has depended in the past, and will continue to depend, on stable long-term, broadly based, quality research. Although the Research Programme is driven by the requirements of customers (e.g. Director of Operations, Director of Commercial Services, Department of the Environment, etc.), it is important to ensure that, in meeting these demands, the ethos of long-term quality research is not compromised by over-commitment to

commercial opportunities giving short-term financial gain. To avoid this the Office's Research Programme will be supported and promoted in a way that enables it to be recognized for its quality and integrity and its prime-mover scientists will continue to be offered attractive career prospects within their speciality.

In summary:

- A lot of challenging meteorological research remains to be done over the coming decade.
- The Meteorological Office offers excellent resources and facilities as well as an exciting research environment in which to pursue this work.
- The tasks are enormous and they depend upon: a stable, long-term research programme, and close national and international co-operation.

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## **An assessment of the surface fluxes from the Meteorological Office numerical weather prediction models. Part I: Momentum**

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### **Summary**

*The ocean and atmosphere interact by exchanging fluxes of momentum, heat and moisture across their boundary. Estimates of these fluxes come from operational numerical weather prediction models. An assessment of the surface momentum fluxes from such models is carried out using fluxes from the Meteorological Office's Fine and Coarse Mesh models, an ocean model of the North Atlantic is also used to assess the ocean response to the NWP fluxes and biases in them.*

### **1. Introduction**

The ocean and atmosphere exchange heat, momentum and fresh water across the ocean surface. Specification of these fluxes serves as a lower boundary condition for atmospheric models and an upper boundary condition for ocean models. The FOAM (Forecasting Ocean Atmosphere Model) group of the Meteorological Office (MO) is developing an ocean model to be used for forecasting studies. This model will require the specification of the surface fluxes, up to 6 days ahead of time, as its upper boundary condition. It has been suggested that, at least in the near future, the best estimates of the surface fluxes will come from NWP (Numerical Weather Prediction) models (Burridge and Gilchrist 1989). Further, they will be the only source of forecast surface fluxes. As a first stage in the development of FOAM an assessment of the surface fluxes from the current MO operational NWP models has been carried out. Results for the momentum fluxes form the contents of this document.

Alves and Foreman (1989) integrated an ocean model using NWP fluxes and compared the results with those

from a similar integration using climatological fluxes. The experiments were carried out for October 1988 and March 1989. They reported that the NWP forced integration developed the observed sea surface temperature (SST) anomalies reasonably well. The lack of a sufficiently accurate observed SST field prevented them from being able to assess the surface fluxes adequately.

There are three main errors that can occur in the surface fluxes from a NWP model. Firstly there is the forecast error. This depends on the ability of the model to represent the real atmospheric situation and to forecast it correctly. It depends on all the model formulations, observations used, data assimilation scheme and indeed on the quality of the fluxes. This topic will not be discussed further and such errors will be ignored as the main interest is in the calculation of the surface fluxes themselves. A second source of errors is the parametrization of the fluxes, for example, how a particular flux can be calculated from the model fields. As will be seen in later sections this is still not fully understood. Thirdly, the model parametrizes the surface

fluxes as functions of the basic model fields; wind, temperature and humidity. Inadequacies in their simulation would lead to errors in the fluxes.

To assess the quality of the surface fluxes an ocean model was used. The aim was to reveal any biases in the momentum fluxes and to quantify the sensitivity of the ocean model to these biases by comparing results from ocean model integrations using NWP momentum fluxes with similar integrations using climatological fluxes. Fluxes from the two MO operational models were compared, together with their parametrizations. A brief discussion of the parametrization of the fluxes in view of recent literature is also included.

A brief description of the operational NWP models used by the MO and a fuller description of how they parametrize the surface momentum fluxes is given in section 2. Section 3 describes the ocean model and the experiments carried out. Results for the momentum fluxes from the ocean model test, including a discussion of the flux parametrizations, are given in section 4. In section 5 a summary is presented and conclusions are drawn. Recommendations are made for future development.

## 2. The NWP models

### 2.1 The MO NWP models

The MO used two operational numerical weather prediction models, described by Bell and Dickinson (1987). The 'Coarse Mesh' (CM) model was global and used a latitude/longitude resolution of  $1.875^\circ \times 1.5^\circ$ . The 'Fine Mesh' (FM) model had twice the resolution of the CM,  $0.9375^\circ \times 0.75^\circ$ , and covered an area from  $30^\circ$  N to  $80^\circ$  N and from  $80^\circ$  W to  $40^\circ$  E. Output from the global CM model was used to supply boundary conditions for the limited-area FM model. Both models used sigma ( $\sigma$ ) coordinates in the vertical ( $\sigma$  = ratio of pressure to surface pressure). Both models were run twice a day, at 00 UTC and 12 UTC. The CM model produced forecasts up to 6 days ahead and the FM model up to 36 hours ahead. Only the first 12 hours of each forecast were used in this study.

From each model, monthly mean fields consisting of the first 12 hours of each forecast were formed for the month of October 1989. The fields available from the NWP archives are shown in Table I indicated by a '✓' and those not available in the model archives are indicated by a 'X'. They will be discussed in later sections.

### 2.2 Parametrization of the surface processes.

The parametrization of the boundary-layer processes is described fully in Bell and Dickinson (1987). A brief summary and recent changes are outlined below. The surface wind stress  $\tau = (\tau_x, \tau_y)$  is defined in terms of bulk aerodynamic formulae. For the CM model the bulk formulae take the explicit form

$$\tau_x = \rho C_D |\mathbf{v}| u_1 \quad (1)$$

$$\tau_y = \rho C_D |\mathbf{v}| v_1 \quad (2)$$

where  $C_D$  is the drag coefficient,  $|\mathbf{v}| = (u_1^2 + v_1^2)^{1/2}$  and  $u_1$  and  $v_1$  are the first model-level horizontal wind components. In the FM model an implicit finite difference scheme (Kitchen 1986) is used for the turbulent fluxes in the boundary layer and the bulk aerodynamic formulae take the form

$$\tau_x = \rho C_D |\mathbf{v}| (\alpha u_1^{t+\Delta t} + (1-\alpha) u_1^t) \quad (3)$$

$$\tau_y = \rho C_D |\mathbf{v}| (\alpha v_1^{t+\Delta t} + (1-\alpha) v_1^t) \quad (4)$$

where  $\alpha = 0.5$  and the superscripts  $t$  and  $t+\Delta t$  refer to successive time-levels;  $\Delta t$  represents a time step.

The drag coefficient  $C_D$  depends on the surface roughness length  $z_0$  and the bulk Richardson number  $Ri_b$ . It is calculated using different empirical functions which depend on the stability of the boundary layer (see Bell and Dickinson 1987). Bell and Dickinson indicate that in the CM model  $z_0$  over the sea was a constant value of  $10^{-4}$  m. For the FM model the surface roughness length  $z_0$  was a variable and was calculated using the Charnock formula (Charnock 1955)

$$z_0 = M u_*^2 / g \quad (5)$$

where  $M$  is a constant (taken to be 0.019),  $u_*$  is the surface friction speed and  $g$  is the acceleration due to gravity.

In the FM and CM models the wind mixing energy (WME) is calculated from the wind stress every time-step using the formula

$$\text{WME} = |\tau|^{3/2} / \rho_s^{1/2} \quad (6)$$

where  $|\tau|$  is the magnitude of the wind stress and  $\rho_s$  is the density of the sea water ( $1025 \text{ kg m}^{-3}$  in the forecast models). The archiving of the data from the forecast models involves compressing each field. The wind mixing energy was over-compressed and low values of the WME were effectively set to zero. For this reason no tests were carried out involving the NWP wind-mixing energy values.

**Table I.** Fields extracted from NWP archives. X = not available.

	FM	CM
Wind-mixing energy	X	X
Wind-stress components	✓	✓
$\sigma$ , wind components	✓	X
10-metre wind components	✓	✓

### 3. Use of an ocean model to assess the surface fluxes

The ocean model used is based on that of Cox (1984) where a leap-frog differencing scheme is used to integrate the primitive equations. Approximations include that of Boussinesq, the hydrostatic assumption, a 'rigid lid' assumption and where the domain boundary crosses open ocean this boundary is assumed to be closed. The model uses regular latitude/longitude horizontal co-ordinates with a grid spacing of  $1^\circ$  throughout. In the vertical, depth coordinates are used with 17 vertical levels which are concentrated in the upper 200 metres. To allow tracers to diffuse along isopycnic surfaces a scheme, which solves the diffusion equation along isopycnics and then transforms back to model coordinates, is used and is based on that of Redi (1982). In the vertical, two mixing schemes are employed. Below the mixed layer the stability dependent scheme of Pacanowski and Philander (1981) parametrizes the eddy diffusivity in terms of the Richardson number, which itself depends on the static stability and vertical shear of the flow. In the mixed layer a scheme similar to that of Kraus and Turner (1967) is used. In this scheme convective mixing takes place when there is surface density increase through cooling or evaporation. After this, and where there is net surface heating, the mixing energy of the wind is used to overcome the stability of the upper layers and mix the more buoyant water downwards. A mixed layer depth is diagnosed as the depth to which mixing occurs.

Surface fluxes of momentum, non-penetrating heat, solar radiation and fresh water are used as the upper boundary conditions for ocean model integrations. Interaction between the ocean and the atmosphere is shown schematically in Fig. 1. Momentum flux is used by the ocean model to drive the Ekman drift currents

and the long-term average wind stress drives the upper ocean circulation. Water near the surface is mixed downwards using the wind mixing energy. Heat is either input or removed from the ocean through the specification of the heat fluxes. The salt budget is modified at the surface by the freshwater flux.

For the month of October 1989 forcing fields were extracted from the NWP archives for each forecast starting at 00 UTC and 12 UTC each day. The T+3, T+6, T+9, and T+12 forecasts from the FM model were used to form 3-hourly averaged forcing fields. For the CM model only the T+6 and the T+12 fields were available. The T+6 was copied and relabelled the T+3 and the T+12 was copied and relabelled the T+9, so forming a set of 3-hourly forcing fields. The fields extracted consisted of the surface wind stress components.

The ocean model's domain covers the North Atlantic from  $30^\circ\text{S}$  to  $80^\circ\text{N}$ . The region covered by the FM is contained within the domain of the ocean model. It is desirable to use the FM model's forcing fields where possible because of its improved physics and higher resolution. To achieve this the FM and CM fields were merged together so that the FM values were used within the FM domain and those of the CM outside the FM domain, with a smoothing applied at the FM boundary. The resulting fields will be from hereon referred to as the 'merged' fields.

The ocean model was started with salinity and temperature fields interpolated from the Levitus (1982) atlas for March. The currents were set to zero. It was integrated for 7 months using climatological forcing fields (wind stress and wind mixing energy — Hellerman and Rosenstein (1983), solar radiation, IR radiation, sensible heat, latent heat and evaporation — Esbensen and Kushnir (1981), and precipitation — Jaeger (1983)). Throughout the integration a relaxation of the surface temperature and salinity back to the Levitus climatology was employed, based on that of Haney (1971). The end product was the starting point for the experiments described below, it being a set of model fields valid for 1 October.

Relaxation of the surface temperature and salinity was switched off for the rest of the experiment. The ocean model was then integrated for one more month, October, still using the climatological fluxes. This formed the control run hereafter referred to as the 'climatological' run. This 1-month integration was repeated replacing the climatological momentum flux with the NWP one. In the following sections this will be referred to as the 'NWP' run or the 'operational' run. Monthly mean fields for temperature, salinity, currents, mixed layer depth and the forcing fields were obtained for each run and compared with the climatological control run. These will be discussed in the section to follow. For the purpose of comparison all fields presented have been linearly interpolated onto the ocean model's grid.

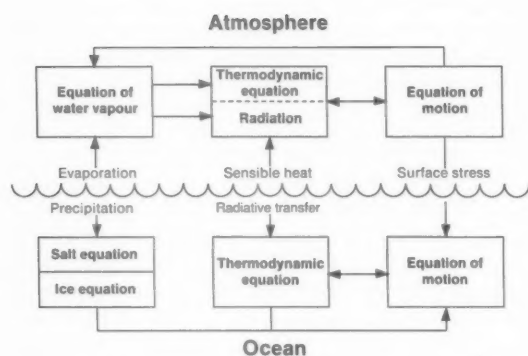


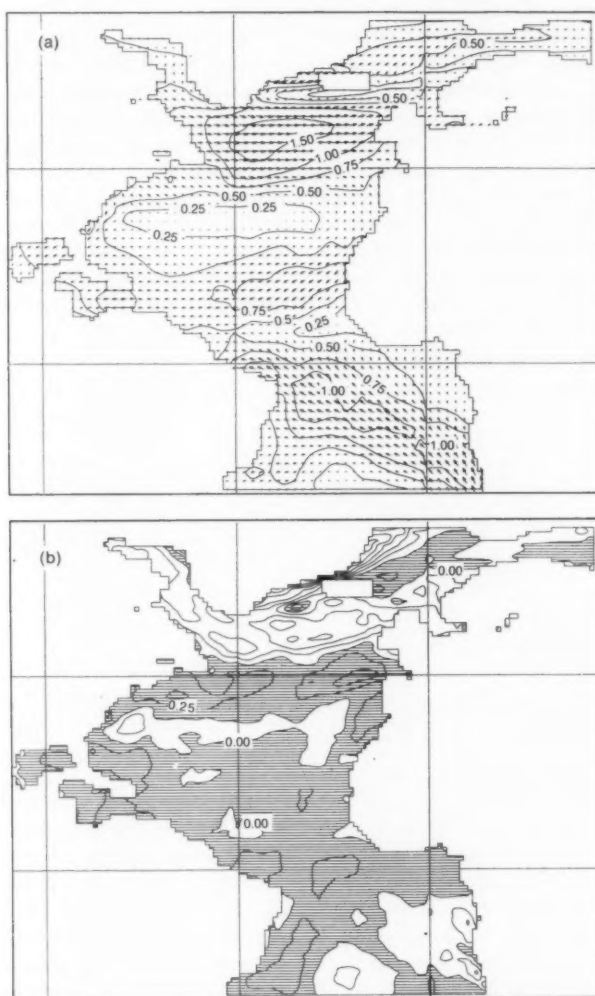
Figure 1. Schematic diagram of the interaction between the ocean and the atmosphere.

## 4. Momentum fluxes

### 4.1 Results

The monthly mean climatological wind stress (Hellerman and Rosenstein 1983) used to drive the climatologically forced ocean model is shown in Fig. 2 together with the monthly mean difference in the magnitude between the merged NWP wind stress and the climatological wind stress. The main areas of strong wind stress are those associated with the South-East Trades (wind stress magnitude exceeding  $0.1 \text{ N m}^{-2}$ ), the North-East Trades (reaching over  $0.075 \text{ N m}^{-2}$ ) and the mid-latitude westerlies of the North Atlantic (reaching over  $0.15 \text{ N m}^{-2}$ ). The wind stress due to the South-East Trades from the NWP models is generally some 25% stronger than the

corresponding climatological value (for example  $0.025 \text{ W m}^{-2}$  stronger where the climatological value is  $0.1 \text{ N m}^{-2}$ ). Near the equator and the area of the North-East Trades, the NWP wind stresses are weaker. In the western equatorial Atlantic the NWP wind stress is some  $0.025 \text{ W m}^{-2}$  weaker in a region where the climatological wind stress is around  $0.05 \text{ N m}^{-2}$ , representing a 50% smaller value. In the North-East Trades differences of up to  $0.025 \text{ N m}^{-2}$  also occur although here this represents only about 30% of the climatological value. In the mid-latitude North Atlantic westerlies the NWP wind stresses have a much larger magnitude, 50% larger, than the climatology. Large departures of the NWP values from the climatology are expected in this region as it is associated with the North Atlantic storm track.



**Figure 2.** (a) Monthly mean climatological wind stress for October 1989; contours at 0.25, 0.5, 0.75, 1 and  $1.5 (\times 0.1) \text{ N m}^{-2}$ , and (b) monthly mean difference between the NWP merged wind-stress magnitude and the climatology for October 1989; contours every  $0.25 (\times 0.1) \text{ N m}^{-2}$ , and negative areas are shaded.

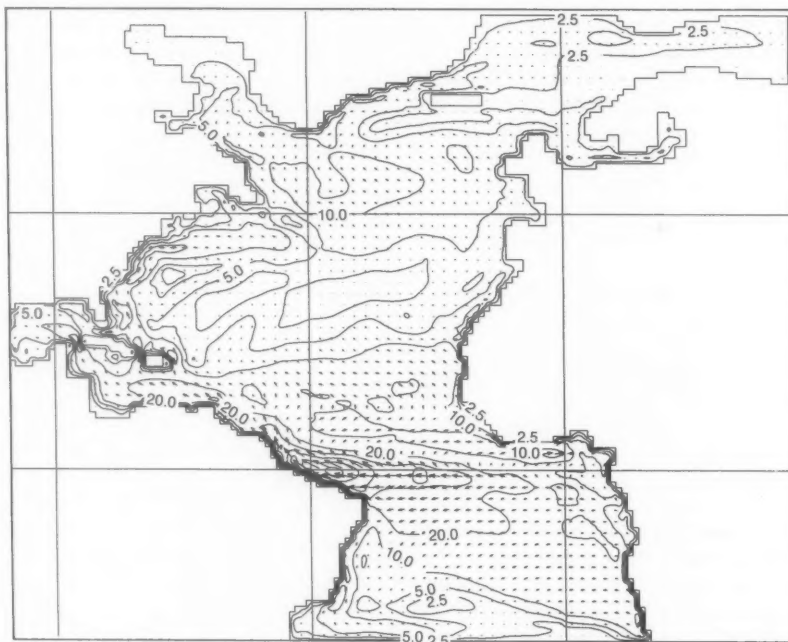
The monthly mean model top-layer current field produced by the climatology forced run is shown in Fig. 3. Strongest currents are those associated with the equatorial current system and the North Atlantic western boundary currents. In the mid-equatorial Atlantic the surface equatorial current has a magnitude of around  $20 \text{ cm s}^{-1}$  and intensifies towards the west to form a western boundary current when it approaches the Brazilian coast, where its magnitude increases to over  $1 \text{ m s}^{-1}$ . The surface Gulf Stream has its maximum strength of  $20 \text{ cm s}^{-1}$  off the coast of USA and separates from the coast near Cape Cod, further north than Cape Hatteras where it is normally observed to leave the coast (a deficiency common to ocean models).

Over short time-scales the wind stress produces near-surface Ekman drift currents superimposed on the main current system. Over longer time-scales (order of a month) the wind stress can affect the upper ocean current structure via the wind-stress curl. The mean monthly differences between the model top-layer currents from the two runs is shown in Fig. 4(a). In the equatorial region the differences in the wind stress between the two integrations of  $0.025 \text{ N m}^{-2}$  introduce appreciable differences in the surface currents. The equatorial current itself is weakened by the reduced wind stress, its magnitude being reduced by up to  $10 \text{ cm s}^{-1}$  (50%) in the mid-equatorial Atlantic and up to  $20 \text{ cm s}^{-1}$  (20%) in the more intense current off the Brazilian coast. For the Gulf Stream, differences of up to  $5 \text{ cm s}^{-1}$  (20%) occur. In the mid-latitude North Atlantic the large wind-stress anomaly produces relatively

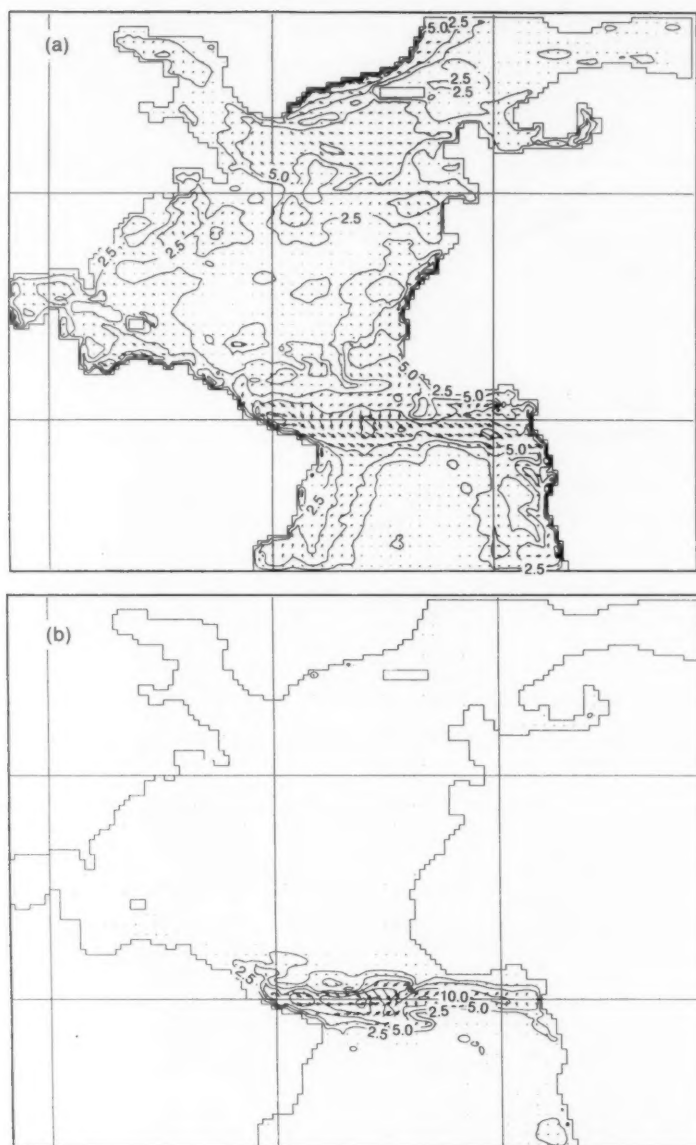
large surface current differences between the two runs which are comparable with the magnitude of the currents themselves.

The relatively large differences in the model top-layer current fields shown in Fig. 4(a) arise as a result of Ekman drift and are limited to the upper 20 metres or so of the ocean. Fig. 4(b) shows the difference in the two current fields at 35 metres (fourth model level). Outside the equatorial latitudes the difference between the two fields is negligible, whereas around the equator there are relatively large vector differences of up to  $20 \text{ cm s}^{-1}$  (50%). This difference extends to depths of over 100 metres and clearly indicates a change in the equatorial current system. It verifies the dependence of the equatorial currents on the relative long-term average wind stress forcing and it shows their sensitivity to changes in the mean wind stress over a period as short as one month.

The difference in the monthly mean SST produced by the two runs is shown in Fig. 5. Outside the equatorial region there is negligible difference except for areas of coastal upwelling. On the equator the modification to the upper ocean current field introduces a warming of up to  $0.8^\circ \text{C}$  of the sea surface. Differences in the temperature structure between the two runs of up to  $1^\circ \text{C}$  exists down to depths of over 100 metres (not shown). This change in the temperature structure leads to a corresponding change in the mixed layer depth which is generally reduced by a few tens of metres in some places (Fig. 6).



**Figure 3.** Monthly mean model top-layer current vector field produced by the climatological control run for October. Contours at 2.5, 5, 10, 20, 40, 60, 100  $\text{cm s}^{-1}$ .

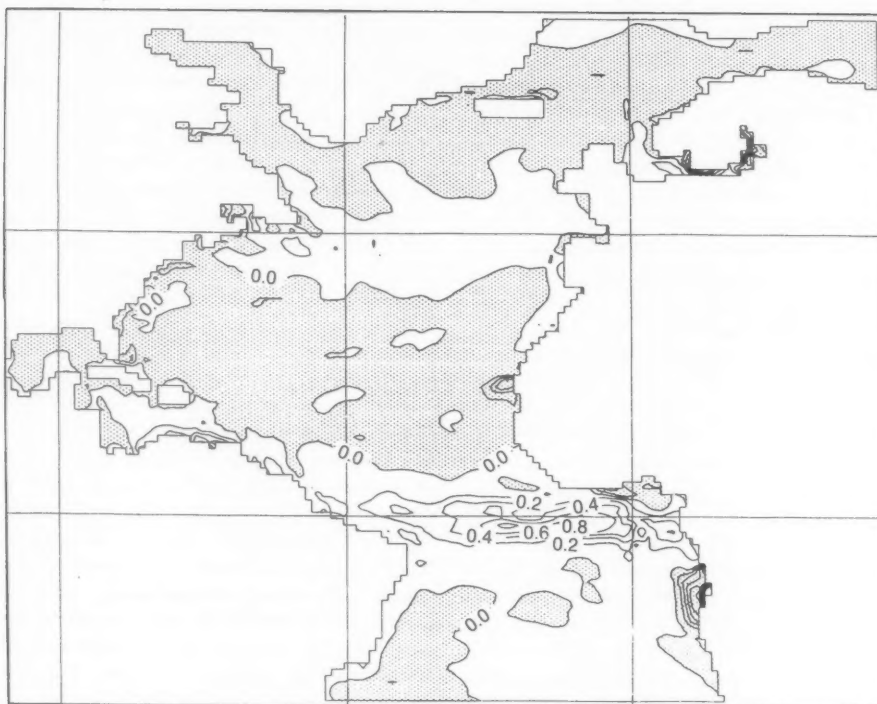


**Figure 4.** Monthly mean difference between the NWP momentum-forced run for October 1989 and the climatological run for (a) the model top-layer current, and (b) the 35-metre current. Contours at 2.5, 5, 10, 20 and 40  $\text{cm s}^{-1}$ .

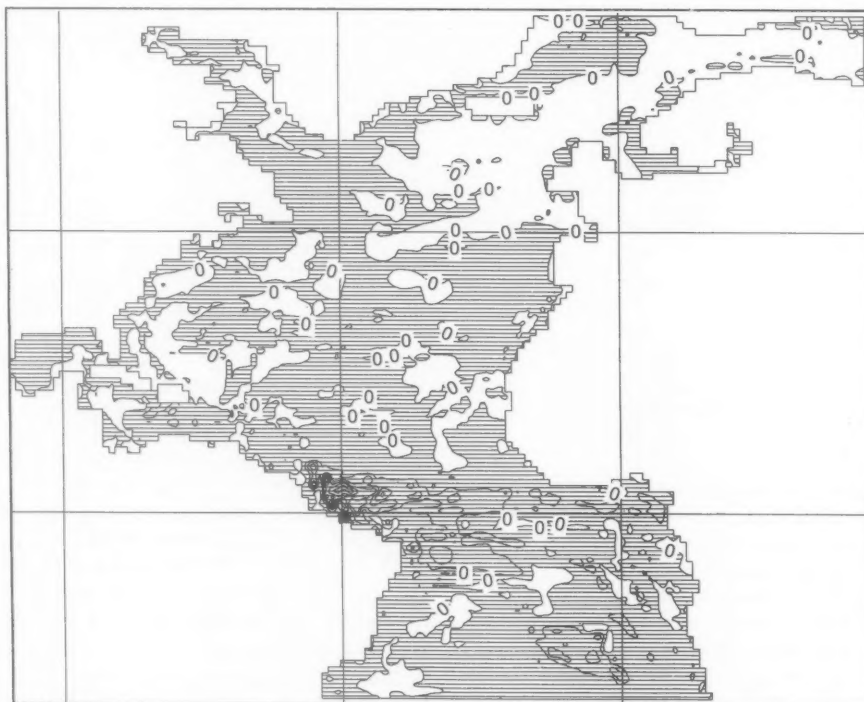
## 4.2 Discussion

Wind stress depends on the wind components and the drag coefficient, equations (1) and (2). Fig. 7 shows the 10-metre monthly mean wind from the CM model for October 1989. Actual sigma 1 wind was not available in the model archives and the 10-metre wind is used throughout this discussion instead. The strongest winds are the Trades and the mid-latitude westerlies. The mean wind speed in the CM model reaches over  $6 \text{ m s}^{-1}$  in the North-East Trades and over  $8 \text{ m s}^{-1}$  in the South-East Trades and the mid-latitude North Atlantic westerlies. Away from the coast (where interpolation errors may

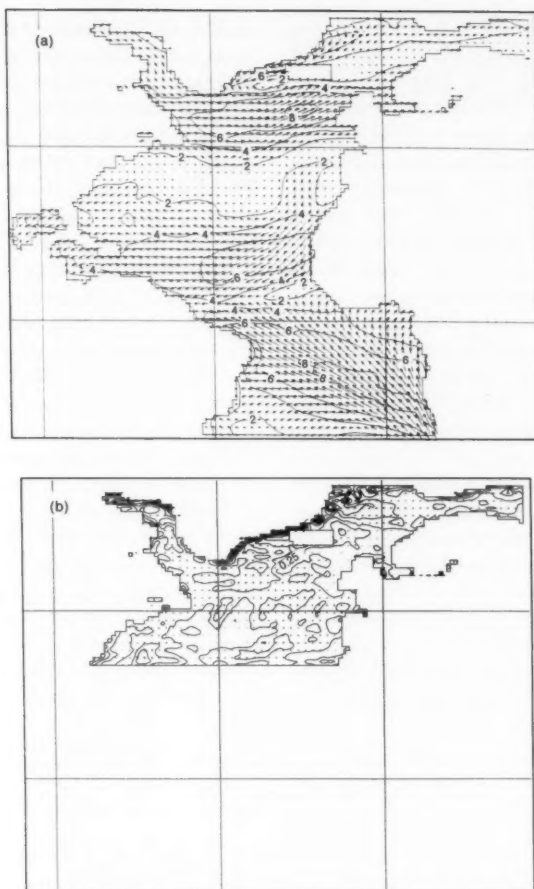
occur) differences of up to  $0.75 \text{ m s}^{-1}$  occur between the two models in an area where the CM wind is around  $6 \text{ m s}^{-1}$ , this corresponding to a difference of just over 10%. Ignoring the dependence of the drag coefficient on the wind speed in the FM model, the wind stress is proportional to the square of the wind speed (equations 1 and 2) and the wind mixing energy is proportional to the cube of the wind speed (equation 6). An uncertainty of 10% in the wind speed (a figure representative of the differences in Fig. 2) would therefore render uncertainties of 20% in the wind stress magnitude and 30% in the value of the wind mixing energy.



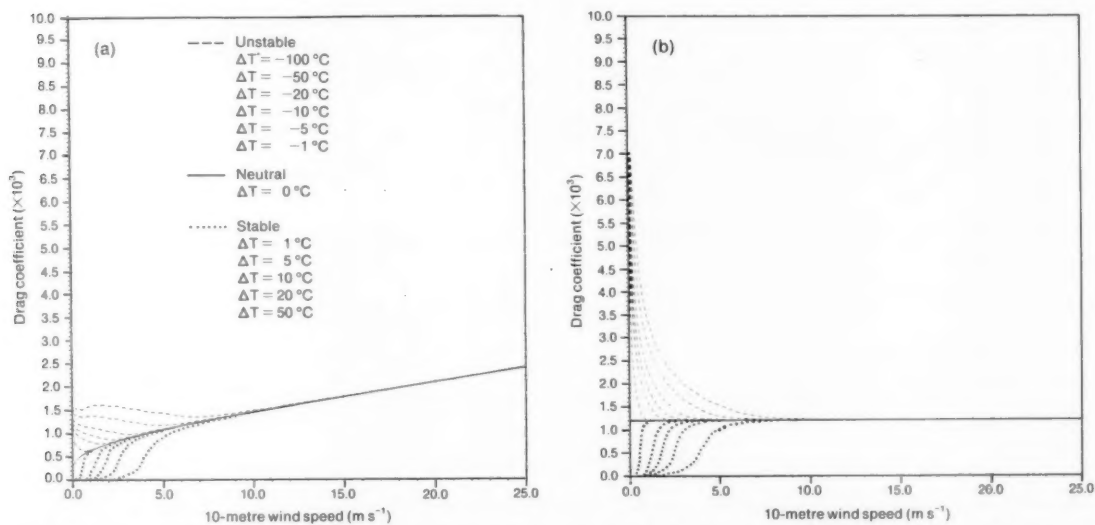
**Figure 5.** SST monthly mean difference between the NWP momentum-forced run and climatological control run for October 1989. Contours every 0.2 °C and negative areas are shaded.



**Figure 6.** Mixed-layer depth monthly mean difference between the NWP momentum-forced run and the climatological control run for October 1989. Contours every 10 metres and negative areas are shaded.



**Figure 7.** (a) CM model's monthly mean 10-metre wind vectors for October 1989; contours every 2 m s<sup>-1</sup>, and (b) vector difference between the FM and CM models' monthly mean 10-metre winds for October 1989. Contours every 0.25 m s<sup>-1</sup>.



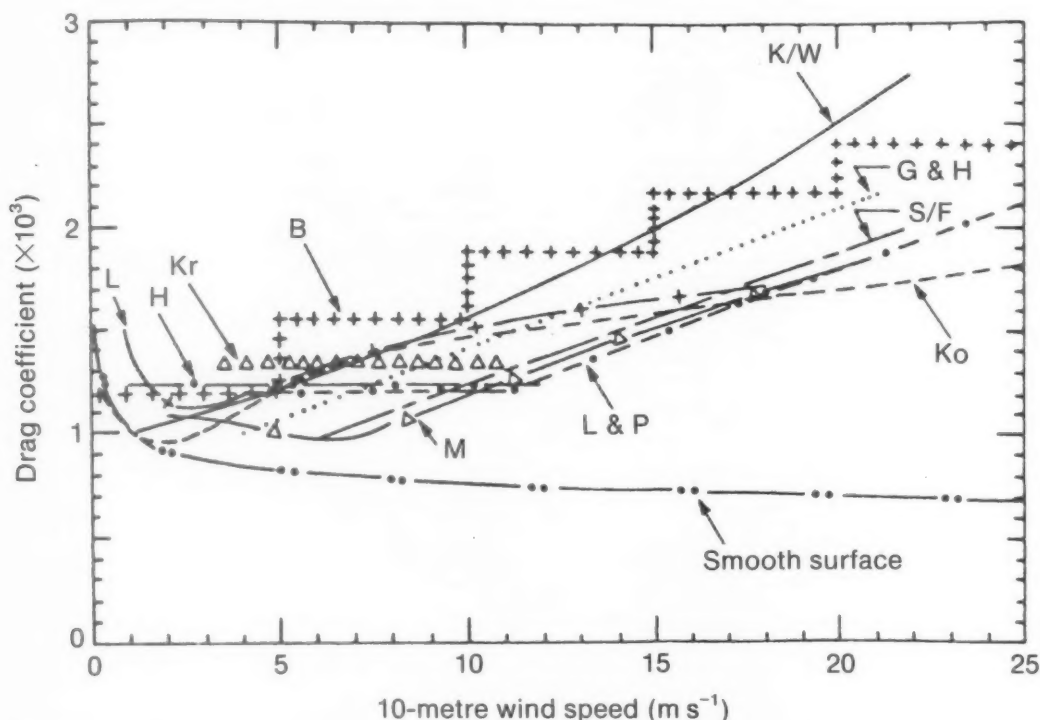
**Figure 8.** Drag coefficient as a function of the 10-metre wind speed for various air-sea temperature differences ( $\Delta T$ ) and zero humidity difference for (a) FM model, and (b) CM model.

Fig. 8 shows the drag coefficient at 10 metres for the FM and CM models as a function of the 10-metre wind for different stabilities ( $\Delta T$ ). The drag coefficients shown are those at 10-metres, although the model uses the drag coefficient at the first sigma level which is at about 30 metres above the ground. The reason for this is to allow for the easy comparison with other authors who use the 10-metre drag coefficient. For wind speeds greater than  $6 \text{ m s}^{-1}$  or so the different stability curves approach that of the neutral curve. The values of  $C_D$  from the two models agree well for wind speeds in the range  $5$  to  $8 \text{ m s}^{-1}$ . For wind speeds greater than  $8 \text{ m s}^{-1}$  the Charnock formula (5) in the FM model causes the drag coefficient to increase with wind speed whereas for the CM model the constant roughness length gives a constant neutral  $C_D$ . For a wind speed of  $25 \text{ m s}^{-1}$  the FM would use a value for  $C_D$  of  $2.4 \times 10^{-3}$ , twice that used by the CM model. It must be emphasized that although in Fig. 7(a) the mean wind speeds do not reach over  $10 \text{ m s}^{-1}$ , the field represents monthly mean values and the individual model time-step values may be much greater than this.

For wind speeds less than  $5 \text{ m s}^{-1}$  the stability dependence becomes important. The Charnock formula (5) in the FM model causes the surface roughness length to tend to zero quadratically with the wind speed. The

neutral  $C_D$  line therefore decreases with wind speed and tends to zero. As an example, the value of  $C_D$  used by the FM model for a wind speed of  $1 \text{ m s}^{-1}$  is about  $6 \times 10^{-4}$ , half that used by the CM model. For stable conditions the difference between the two models' value of  $C_D$  is mainly due to the decrease in the neutral value in the FM model. Under slightly unstable conditions the value of  $C_D$  is very close to its neutral value and the difference between the two models is more or less due to the difference in the neutral value as a result of using the Charnock formula for the FM model. The differences between the two grow as stability and wind decrease. For conditions of free convection ( $Ri_b$  less than  $-100$ ) the CM uses a value for  $C_D$  of around  $1.5 \times 10^{-3}$ , approximately four times larger than that used by the FM model. This is simply a consequence of using the Charnock formula for low wind speeds.

Parametrization of the drag coefficient has been reviewed by Garratt (1977). Later Blanc (1985) reviewed several empirical schemes used by different authors. His results for the neutral and slightly unstable drag coefficient are shown in Fig. 9. The variation between the schemes is large, for example the drag coefficient for a  $10 \text{ m s}^{-1}$  wind speed varies from  $1.2 \times 10^{-3}$  to  $1.9 \times 10^{-3}$ , a 50% difference. This indicates the difficulty in parametrizing the drag coefficient and the large



**Figure 9.** Drag coefficients for ten selected schemes and for a smooth surface under neutral or slightly unstable conditions as a function of the 10-metre wind speed (from Blanc 1985). Sources are: K/W = Kitaigorodskii *et al.* (1973), Wu (1980); Ko = Kondo (1975); G & H = Garratt (1977), Garratt and Hyson (1975); B = Bunker (1976); Kr = Krügermeyer (1976); S/F = Smith (1980), Friehe and Schmitt (1976); H = Hasse *et al.* (1978); L = Liu *et al.* (1979); M = Masagutov (1981); L & P = Large and Pond (1981, 1982).

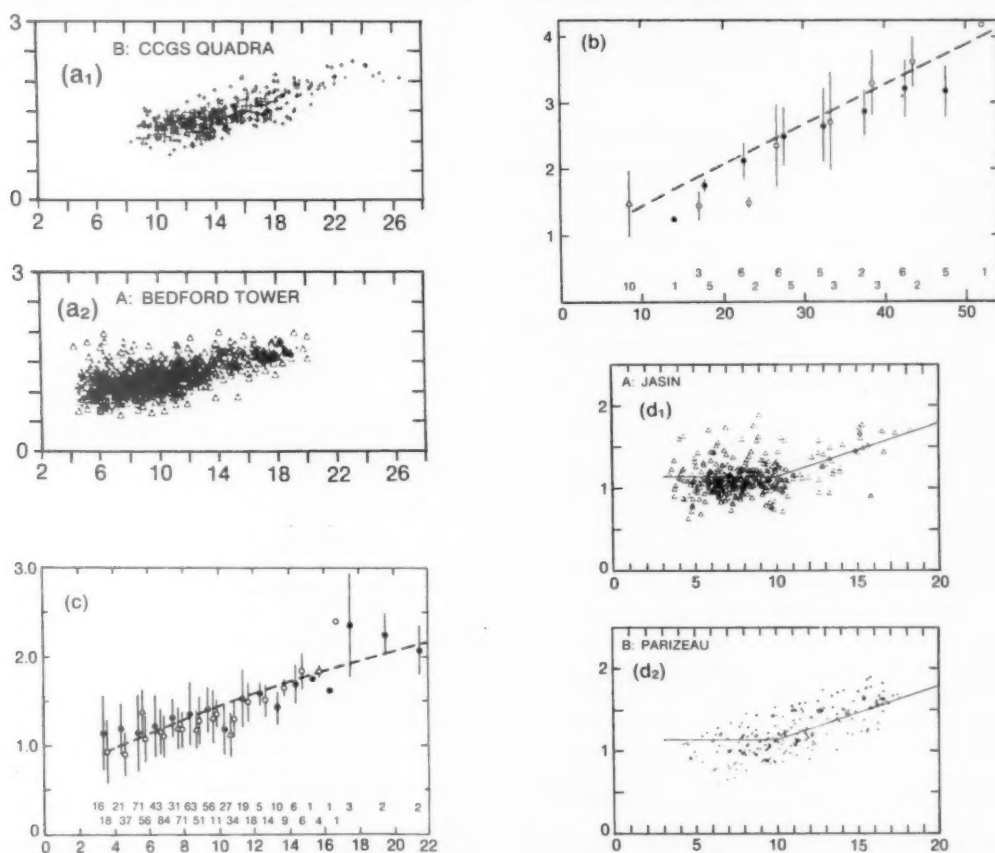
differences in the various empirical formulae. For all the empirical relations shown in Fig. 9 the neutral drag coefficient increases with wind speed for strong winds. The CM model has a constant  $C_D$  of  $1.2 \times 10^{-3}$  which deviates largely from those of Fig. 9 for wind speeds greater than  $10 \text{ m s}^{-1}$ . As an example, for a wind speed of  $20 \text{ m s}^{-1}$  the CM uses a value for  $C_D$  of  $1.2 \times 10^{-3}$  while the average of the schemes represented in Fig. 9 is  $2 \times 10^{-3}$ , i.e. 40% larger. For wind speeds less than  $10 \text{ m s}^{-1}$  the value used by the CM model is in good agreement with the other parametrizations. The use of the Charnock formula in the FM model produces a drag coefficient which increases with wind speed. For wind speeds greater than  $5 \text{ m s}^{-1}$ , the FM model's drag coefficient is in good agreement with that of the authors shown in Fig. 9. For low wind speeds, less than  $5 \text{ m s}^{-1}$ , the FM  $C_D$  decreases with wind speed, such is not the case with the other authors. As an example, the average value for  $C_D$  from Fig. 9 for a wind speed of  $1 \text{ m s}^{-1}$  is  $1.1 \times 10^{-3}$ , but the FM uses a value of  $0.6 \times 10^{-3}$ , a 45% underestimate. As regards the empirical relations of Fig. 9, the FM agrees well for large wind speeds but underestimates the value of  $C_D$  for light winds. On the

**Table II.** Average neutral drag coefficient from various sources ( $\times 10^3$ ). The letters refer to different parts of Fig. 10.

Source	Wind speed ( $\text{m s}^{-1}$ )				
	5	10	15	20	25
a <sub>1</sub>	—	1.2	1.5	1.8	2.1
a <sub>2</sub>	1.2	1.2	1.6	1.7	—
b	—	1.2	1.6	1.9	2.2
c	1.0	1.3	1.7	2.2	—
d <sub>1</sub>	1.2	1.2	1.4	1.8	—
d <sub>2</sub>	1.2	1.2	1.5	1.8	—
Average	1.2	1.2	1.55	1.85	2.15
FM	1.0	1.4	1.8	2.1	2.4
CM	1.2	1.2	1.2	1.2	1.2

other hand, the CM model agrees well for light winds but underestimates the value of  $C_D$  for strong winds.

Fig. 10 shows several sets of observational measurements of the drag coefficient. For each of these plots and for wind speeds of 5, 10, 15, 20 and  $25 \text{ m s}^{-1}$  an average value was estimated and an overall average calculated as shown in Table II. The values from the FM and CM models are also shown.



**Figure 10.** Experimental plots of the drag coefficient ( $\times 10^3$ ) as a function of wind speed ( $\text{m s}^{-1}$ ). (a) and (b) are from Large and Pond (1981), and (c) and (d) from Garratt (1977).

As already discussed the CM agrees well for wind speeds up to  $10 \text{ m s}^{-1}$  but badly for stronger winds. For light winds the FM model's  $C_D$  decreases with wind speed but this is not observed for  $C_D$  at a wind speed of  $5 \text{ m s}^{-1}$ . The table does however show that for the wind speeds of 10, 15, 20 and  $25 \text{ m s}^{-1}$  the use of the Charnock formula overestimates the drag coefficient by 10–15% when compared with the average observed values. However, it must be emphasized that the observed values have a large spread and that only the mean value has been considered in the above table.

Use of the Charnock formula to parametrize the surface roughness length has been discussed in detail by Hasse (1986). The failure of this formula to represent the roughness length for light winds, as seen from the FM drag coefficient, arises as a result of the flow becoming smooth and viscous effects coming into operation. Hasse (1986) suggests that for aerodynamically smooth flow the surface roughness should be proportional to the viscosity and inversely proportional to the friction velocity. This would imply that the drag coefficient would increase with decreasing wind speed for light winds. There is little *in situ* experimental evidence to support this except for laboratory experiments. For large wind speeds Hasse concludes that the Charnock formula is an attempt to represent a very complex interaction between the air, sea and waves in a simple formula.

Further development in the parametrization of the surface roughness length, and therefore the neutral drag coefficient, requires the consideration of the influence of the sea state on the atmospheric flow and vice versa. Geernaert (1987) indicates that there is evidence that the drag coefficient decreases with increasing wave fetch and/or increasing water column depth. He also suggests that the neutral drag coefficient exhibits a weak dependence on wind speed for open ocean conditions but exhibits a strong dependence for limited conditions of fetch and/or depth. Geernaert (1988) listed conditions for which wave-induced variations of the drag coefficient have been observed. There have been several attempts to parametrize the surface roughness using sea state parameters (for example Kitaigorodskii (1973), Hsu (1974), Huang and Long (1981), Byrne (1982), Donelan (1982), Geernaert *et al.* (1986), Toba and Koga (1986) and Toba *et al.* (1990)). Toba *et al.* (1990) found that in storm conditions the drag coefficient can be larger by a factor of two or three than the value predicted by the Charnock relation. Geernaert (1988) compared four wave-dependent parametrizations of the surface roughness, they being those of Kitaigorodskii (1973), Byrne (1982) and Donelan (1982), and a fourth which used a generalized version of the Charnock formula incorporating wave parameters. He concluded that the parametrization scheme of Kitaigorodskii (1973) best fitted the experimental data from near

coastal locations. His results showed that the drag coefficient under strong winds increases with decreasing fetch and decreasing depth of water. Later, Janssen (1989) found there to be a strong dependence of the drag coefficient of air flow over sea waves on the wave age. For a young wind sea (small wave age) there was a strong coupling between wind and waves, whereas hardly any coupling was apparent for old wind sea. This dependence of the neutral drag coefficient on sea state explains some of the scatter in the observed values shown in Fig. 10, although a large proportion of the scatter is attributed to experimental uncertainties (Geernaert 1987).

For the new MO NWP 'unified model' the surface roughness will be initially parametrized using the Charnock formula but it will be constrained to remain at or above  $10^{-4}$  metres. This leads to a neutral drag coefficient with the same values as that of the FM for strong winds, but having a minimum of  $1.2 \times 10^{-3}$  for light winds.

## 5. Summary and conclusion

The wind stress from the NWP models when compared with the climatological values showed large differences which were up to 50% of the climatological value. Over the tropical ocean, apart from limited areas within the Trade winds, the CM wind-stress magnitude was less than that of the climatology. In the west equatorial Atlantic the CM wind stress was up to 50% less than the climatology. These differences introduced anomalies in the surface current due to Ekman drift which are superimposed on the basin-scale circulations. The equatorial current system, which is driven by the longer term (order of one month) wind-stress curl, was reduced by up to 50% due to the lower magnitudes of the wind stress in the CM equatorial latitudes.

Comparison of the FM and CM 10-metre winds showed an uncertainty of 10% in the wind magnitude which leads to an uncertainty of 20% in the wind stress magnitude and 30% in the wind mixing energy. The wind mixing energy from the NWP models was not used in this study due to compressing problems while archiving the NWP model output.

Published values of the drag coefficient differ by over 50%. The average of the empirical results considered agree well with the FM and CM values for wind speeds in the range  $5$  to  $8 \text{ m s}^{-1}$ . For stronger winds the values of  $C_D$  were observed to increase with wind speed. The CM underestimates the values of  $C_D$  for strong winds as it uses a constant value. The FM uses the Charnock formula to parametrize the surface roughness length as a function of wind speed. Comparison with experimental results suggest that the FM overestimates the value of  $C_D$  by 10% to 15% for strong winds, although the experimental results showed a large scatter. For light winds the published values for the neutral  $C_D$  either

remained constant in good agreement with the CM value of  $1.2 \times 10^{-3}$  or increased slightly with decreasing wind speed. This was underestimated by the FM model which reduces the value of the neutral  $C_D$  to zero with the wind speed.

Geernaert (1988) suggested that the drag coefficient depends on the sea state and therefore on wave parameters such as fetch and water column depth. He concluded that the dependence of the neutral drag coefficient is less for the open ocean than for near coastal areas where the wave fetch is smaller and the water column depth is less deep. Janssen (1989) found that the drag coefficient additionally depended on wave age. Toba *et al.* (1990) stated that in storm conditions the drag coefficient can be up to two or three times larger than that when the Charnock formula is used.

A major factor in the determination of wind stress is now thought to be the influence of surface waves on the sea. Improvements to the simulation of wind stress are therefore most likely to arise from a parametrization of the drag coefficient which takes account of waves. The only satisfactory means of doing this is to couple a wave model to the atmosphere forecast model.

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## Satellite photographs — 27 June 1991 at 0805 UTC

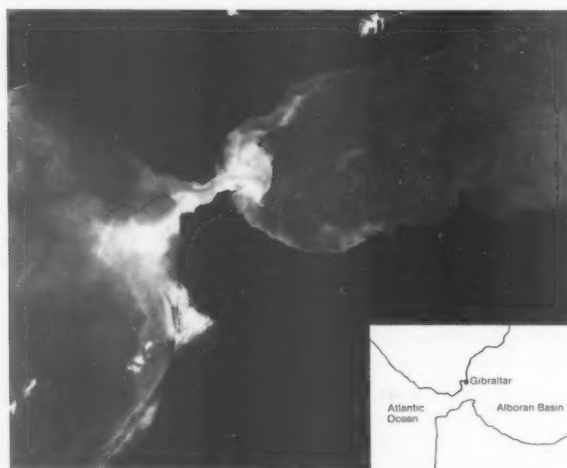
The NOAA-10 infra-red image (Fig. 1) illustrates the pattern of sea surface temperature near the Strait of Gibraltar and the Alboran Basin. The image has been 'enhanced' so that the whole grey-scale range (from black to white) occurs within a few degrees Celsius (approximately 17–22 °C) — corresponding to the range of sea surface temperatures. The visible image taken at the same time (Fig. 2) indicates that only a few patches of cloud are present over the sea, and hence confirms that almost all the structure seen over the sea in the infra-red image is due to variation in the sea temperature.

The main feature is the region of cold water close to the Strait of Gibraltar. Daily inspection of infra-red images suggests it to be commonly observed, particularly

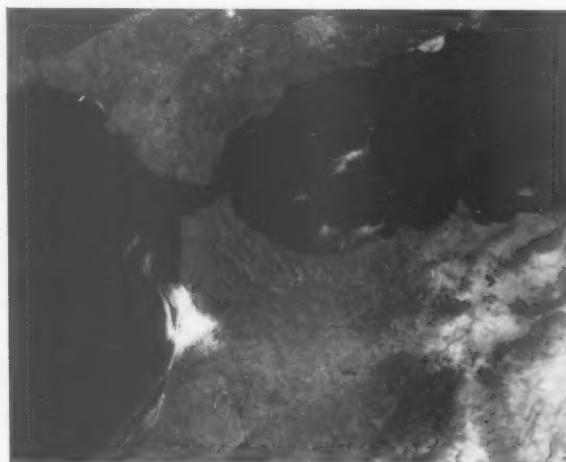
during the summer months, although there are often significant day-to-day differences in its pattern. In the Alboran Basin, large anticyclonic gyres are normally present which sometimes draw in cold water from the Strait of Gibraltar.

The cold sea can have significant effects on the weather. For example, at Gibraltar, the highest incidence of sea fog occurs in August. A change of wind direction to an easterly bringing moisture-laden air from the Alboran Basin frequently results in either fog or very low cloud, whereas onshore winds at observing stations in the Alboran Basin away from the region of cold water do not lead to these conditions.

G.A. Monk



**Figure 1.** NOAA-10 infra-red image for 0805 UTC on 27 June 1991. The insert shows the places mentioned in the text.



**Figure 2.** As Fig. 1 but visible image.

*Photographs by courtesy of University of Dundee*

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